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Josephson heterodyne detection at high thermal background levels

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Point-contact Josephson junctions with a submicron contact diameter have been used as high-frequency mixers (170–220 GHz) under high thermal background conditions. The junction is formed across a full height (0.56×1.06 mm^2) waveguide between a 3–5-μm thick Nb whisker and a 0.2-mm diam Nb center conductor of a coaxial line. The best single-side band mixer-noise temperature that was measured is 165 K ($\pm$ 25%) with a corresponding single-side band conversion efficiency of 0.36 ± 0.03 (a loss of 4.5 ± 0.4 dB) at a signal frequency of 185 GHz, including losses in the coupling horn and the waveguide. The performance was measured with the hot-cold source technique. The effects of nonheterodyne response in that situation were investigated in detail. The junctions have been operated in a coherent receiver that can be used on a telescope with only small adaptations. The instantaneous bandwidth of the receiver is about 20 GHz.

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I. INTRODUCTION

Josephson junctions have proved[1–3] to be very efficient mixers in mm wave heterodyne detectors. Although their intrinsic noise is significantly above the thermal noise limit[4,5] they show much lower mixer-noise temperatures than existing cooled Schottky-diode mixers.[6] It would therefore be a definite advancement if a Josephson mixer could be incorporated in a receiver that can be used on a telescope. Although the recent development of superconductor-insulator-superconductor tunnel junctions as quasiparticle mixers[7–9] is very promising, it is not impossible that at frequencies above 200–300 GHz the advantages of point contacts over those of evaporated tunnel junctions will favor the use of point-contact Josephson junctions.

In this paper, results of niobium-niobium point-contact Josephson junctions as a mixing element in a 170–220 GHz heterodyne receiver using an externally generated local oscillator (LO) are presented. The junctions are operated under high thermal background conditions (no cold attenuators at the signal frequency), as is the case in an operational receiver. The receiver is developed such that it is ready for use on a telescope.

The quality of the total receiver and of the conversion efficiency η and noise temperature T_m of the mixer have been determined using a blackbody thermal source at two different temperatures as a signal source. However, especially with Josephson junctions one has to be very careful using this hot-cold method because a strong nonheterodyne response can occur which can be confused with the heterodyne response. This may either lead to a severe overestimate or a severe underestimate of the performance of the mixer.

The most familiar type of nonheterodyne response[10] occurs when a junction is dc biased from a high impendance source. However, it will be shown that also in the case of a dc-voltage bias a very large nonheterodyne response can occur for contacts with a relatively high surface pressure. These junctions have normalized differential resistance (R_d/R) values equal to or larger than predicted by the Resistively Shunted Junction (RSJ) model.[5] This can be explained by a small hysteresis in the averaged current-voltage (I-V) curve, which is hidden by thermal noise rounding.[11,12]

It will be shown that Josephson junctions which lack all hysteresis can be produced with Nb whiskers with a diameter of about 5 μm. These junctions have R_d/R values which are much lower than predicted by the RSJ model; however, they show a high conversion efficiency ($\eta \simeq 0.4$) and low values of $T_m \simeq 200$ K around 200 GHz, while no nonheterodyne response is present when they are voltage biased.

From the measurements on these two types of junctions it can be concluded that it is always necessary to measure the spectrum of the hot-cold heterodyne response of a Josephson junction (e.g., with a Michelson interferometer) to certify the absence of nonheterodyne response, also when the junction is dc-voltage biased. Because of the absence of these spectral measurements on most Josephson heterodyne receivers that have been reported in the literature, some of these results[13,14] must be looked upon with suspicion.

The design of the mixer is discussed in Sec. II and the rf and intermediate frequency (i.f.) sections of the total receiver are described in Sec. III. In Sec. IV the characteristics of our junctions are discussed. The calibration of the total receiver-noise temperature T_r and the calculation of η and T_m of the mixer from the hot-cold measurements is treated in Sec. V. In Sec. VI the nonheterodyne response is described that can occur even when the junction is voltage biased. The mixer performance of our low-pressure-type contacts is presented and compared with the theory in Sec. VII.

II. THE MIXER

A cross section of the mixer is shown in Fig. 1. It consists of a Nb detector block with a 0.56×1.06 mm^2 rectangular waveguide, which is made through it using the spark-

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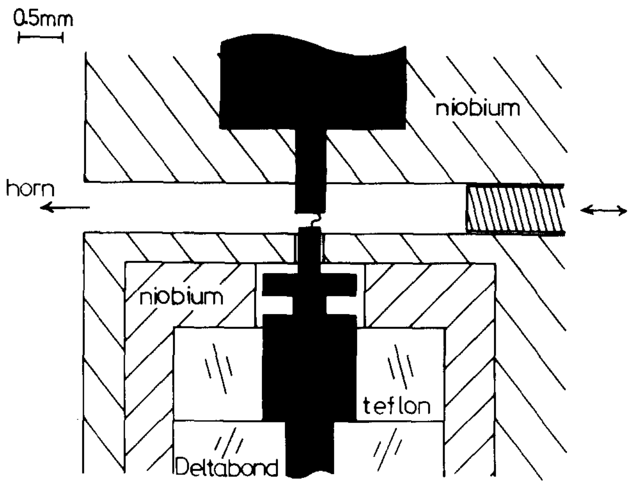

FIG. 1. Cross section of the mixer mount. The waveguide dimensions are 0.56×1.06 mm^2. The coaxial line has a choke in it to confine the rf signal to the waveguide; its dimensions are to scale. The waveguide is terminated with an adjustable back-short.

erosion technique. The waveguide wall was electropolished[15] in a solution of 85% pure H_2SO_4 and 15% HF (conc. 40% in H_2O) to remove the severely damaged surface layer.

The point-contact Josephson junction is made between the 0.2-mm diam Nb central conductor of the coaxial line (the anvil) and a 3–5-μm diam Nb whisker. The wire for the whisker is obtained by electropolishing[15] of a 25-μm diam wire. It is then point-welded under tetrachloromethane to the 0.3×0.9 mm tip of a 2-mm diam Nb pen and shaped such that it acts like a spring. The whisker is cut to the necessary length with a very small chisel such that the top angle of the point is about 30°. The small ravels that exist at the point after cutting are removed by electropolishing it for several seconds. The radius of curvature of the point is roughly 2 μm in one dimension and about 0.4 μm in the other. It is found experimentally that for a compression of the spring of about 10 μm and a ratio of the size of the spring to the diameter of the wire larger than about 15–20, the pressure in the contact is so low that only a small plastic deformation takes place. The surface area of the junction is then smaller than about $0.5 \times 1.0\,\mu m^2$ for a 5-μm diam whisker. The surface of the anvil is electropolished for several minutes to decrease the size of the surface irregularities to smaller than about 0.5 μm. Both the whisker and the anvil are etched in HF to remove the oxide layer that exists on the surface after electropolishing. The junction is then made at room temperature after only several minutes of oxidation in air, and cooled to 5 K within an hour. If necessary, the junction can then be broken and remade by raising and lowering of the post.

The Nb anvil is fitted with an rf choke to prevent leakage of rf signal from the waveguide. The choke effectively lowers the rf impedance at the entrance of the i.f. coaxial line to such a low value compared with the waveguide and junction impedances that the rf signals are undisturbed by the hole. The choke is shown to scale in Fig. 1 and is an improvement[16] over a series of $\lambda_{rf}/4$ long, low and high impedance coaxial sections. It has a rejection ratio greater than 24 dB at 160–240 GHz and greater than 22 dB at 320–480 GHz for the fundamental rf frequency and its second harmonic, respectively.[16] The first section of coaxial line is made in a separate Nb cylinder. Apart from the rf choke it consists of two parts. First, a 1-mm long 50-Ω coaxial line with a teflon dielectric, and then a 3-mm long 50-Ω coaxial section where the anvil is cast in Deltabond[17] epoxy. The Deltabond section ensures a good thermal contact between the anvil and the mixer block. The teflon section is a barrier between the Deltabond and the etching fluid which would be absorbed in the Deltabond and contaminate the junction upon evacuation of the cryostat. The cylinder is made of Nb because it is highly resistant to HF which is used to etch the anvil. It is glued[18] to a slightly adapted sub miniature series A (SMA) coaxial chassis connector.

III. THE RECEIVER

A. The rf system

The receiver is designed such that it is compatible with a telescope with only small external adaptations. It is built in an all metal cryostat[19] that contains 0.8 ℓ of liquid nitrogen (LN_2) and 1.1 ℓ of liquid helium (LHe). Radiation is fed into the waveguide with a circular horn. An adjustable teflon lens just outside the dewar transforms the f/1.5 beam of the horn to an approximately parallel one. The mixer is protected from short-wavelength thermal radiation by two cooled filters (see Table I) but no attenuators are present at the signal frequency. The LO at 180 ± 6 GHz and 224 ± 8 GHz is obtained by frequency doubling the output of two Varian klystrons. It is coupled to the junction by means of a 100-μm thick mylar beam splitter with a reflection of $28 \pm 2\%$ and a transmission of $72 \pm 2\%$, at 200 GHz. This large reflection coefficient is necessary because only a doubler with a very low efficiency is at our disposal.

The noise temperature T_r of the receiver has been measured with the hot-cold method. The receiver is then alternately exposed to radiation from blackbody sources (Eccosorb AN-72) at 294 and 77 K, respectively (with an assumed emission coefficient of 1). If the receiver is used on a telescope, the available LO power is increased by using a more efficient doubler. A much thinner mylar beam splitter can then be used, resulting in a much higher transmission of the signal. T_r will therefore be related to the effective signal-temperature difference in front of the Teflon lens: 294 K for the hot source and $0.72 \times 77 + 0.28 \times 294 = 138 \pm 3$ K for the cold source.

In addition to T_r it is also desirable to measure the performance of the Josephson mixer itself so that it can be com-

TABLE I. The attenuation and reflection values (at 180 GHz) of the components between the outside of the cryostat and the horn, with their respective physical temperatures.

	T (K)	atten (%)	refl (%)
Teflon lens	294	10 ± 2	6 ± 2
TPX vacuum window	294	4 ± 2	6 ± 2
Black polyethylene	90 ± 10	5 ± 2	1 ± 1
CdO embedded in polyethylene	10 ± 5	5 ± 2	6 ± 2

pared with theoretical calculations. However, because of a lack of mm wave equipment it was not possible to measure the efficiency of the horn and the losses in the mixer block. Therefore the mixer noise temperature T_m and the conversion efficiency η that are calculated include the effects of these two coupling losses. The effective source temperatures seen by the mixerblock-horn combination can be found using the data from Table I; we find for the hot source 235 $\pm$ 10 K and for the cold source 133 $\pm$ 10 K.

B. Intermediate frequency system

The first stage of the amplification chain is a 4.75–5.0 GHz room-temperature parametric amplifier (AIL model P544) with a noise temperature of 80 K. The total i.f. attenuation between the SMA connector on the mixer block and the parametric amplifier is 1.5 $\pm$ 0.1 dB. The main contribution to this attenuation is from a 200-mm-long section of BeCu coaxial line (UT-T-85-50-B-B) that is used to reduce the heat input to the LHe bath to about 30 mW.

An interference of the pump frequency of the parametric amplifier with the junction, as found by Adde *et al.*,[20] does not occur. This may be due to the high frequency of the pump (50 GHz), which is rather strongly attenuated by the coaxial line, and to which the junction is less sensitive than to lower pump frequencies used in some other types of parametric amplifiers.

The i.f. system is calibrated by replacing[2,4] the Josephson junction with a point contact between two normal metals (copper), and measuring the noise-output power $P_{\text{i.f.}}$ as a function of the resistance value R of the contact, both at 5 and 77 K. Since $\omega_{\text{i.f.}} \ll k_B T/\hbar$ where k_B and $2\pi\hbar$ are Boltzmann and Planck constants, respectively, $P_{\text{i.f.}}$ is a linear function of temperature T and can be given by $P_{\text{i.f.}} = AT + B$, where A and B are functions of R. From this an effective output noise temperature,[2]

$$T_{\text{out}} = (P_{\text{i.f.}} - B)/A \tag{1}$$

can be determined for a Josephson junction by measuring $P_{\text{i.f.}}$ and the differential resistance $R_d = d\bar{V}/d\bar{I}$, which is the i.f. output impedance[5] of the junction, and using A and B for $R_{\text{i.f.}} = R_d$ ($\bar{V}$ and $\bar{I}$ are the time-averaged voltage across and current through the junction, respectively). The uncertainty in T_{out} is estimated to be $\pm$ 1 K plus 2% of T_{out}.

The noise temperature $T_{\text{i.f.}}$ of the i.f. system, at the junction, has also been calculated from the calibration. It reaches a minimum of 180 $\pm$ 5 K for $R = 50 \pm 10\ \Omega$, where the match between the mixer and the amplifier is almost ideal.

IV. JUNCTION CHARACTERISTICS

The typical product of the zero-voltage Josephson supercurrent I_c and the normal-state resistance R for our low-pressure contacts (see Sec. II) is 1.2–1.8 mV for resistance values of about 50 Ω. This corresponds to about 0.5–0.75 of the theoretical maximum I_cR product[21] for Nb-Nb junctions. The normalized signal frequency $\Omega_s = \hbar\omega_s/2eI_cR$ is then 0.2–0.4 for a signal frequency of 170–220 GHz. These values of Ω_s are optimum[5,22] for heterodyne detection. The resistance value of a newly made junction is usually about 100 Ω. It can be reduced to a desired value by burning in of the contact.[23] The I_cR product usually increases 10–20% for a reduction of R from 100 to about 30 Ω. The *I-V* curves of low-pressure junctions show no sign of hysteresis. A typical *I-V* curve is shown in Fig. 2. The maximum value of R_d/R is usually much lower than predicted by the RSJ model[5] and quite often smaller than unity, as was also observed by others[2] for resistance values above 50–80 Ω. This is also the case when I_c is reduced by rf radiation. Notwithstanding the deviating behavior of R_d, these low pressure junctions are excellent high-frequency mixers (see Sec. VII).

When the surface pressure in the contact is increased by decreasing the ratio of the size of the spring and the diameter of the whisker to about 10 or less, the junctions almost always have a slightly hysteretic *I-V* curve. In this case it is even easier to obtain good I_cR products (up to 2.5 mV for a 10-Ω junction). Whether this small hysteresis is caused by heating effects can be inferred from a paper by Tinkham *et al.*[24] The temperature in the center of a Josephson junction with a three-dimensional cooling geometry is given by[24]

$$T_j = [T_b^2 + 3(e\bar{V}/2\pi k_B)^2]^{1/2},$$

where T_b is the temperature of the mixer block and $\bar{V}$ is the average voltage across the junction. At a halfway point along the bias voltage on the step caused by the LO at about 200 GHz, $T_j = 5.04$ K for $T_b = 5$ K, and $\bar{V} = 2{*}\ 10^{-4}$ V. This suggests that no significant influence exists on the value of the supercurrent, which is confirmed by the power dissipation P in the junction. With $I_c = 30\ \mu$A, $R = 50\ \Omega$, and $\bar{V} = 2{*}\ 10^{-4}$ V, we have $P = 3{*}\ 10^{-8}$ W. The normalized critical current is then given by[24] $\exp[P/P_0] = 0.997$, where P_0 is assumed to be 10^{-5} W for which the behavior of our LO-induced step heights is in rather good agreement with the calculations of Tinkham *et al.*[24] From these values it can be concluded that the usually small hysteresis is not induced by heating and must instead be caused by a capacitance in the junction. This can be made plausible as follows. For this type of whisker the sharpened point of the whisker usually shows some flattening of the order of 1–2 μm when the cryostat is reopened. At the same time the hysteresis tends to

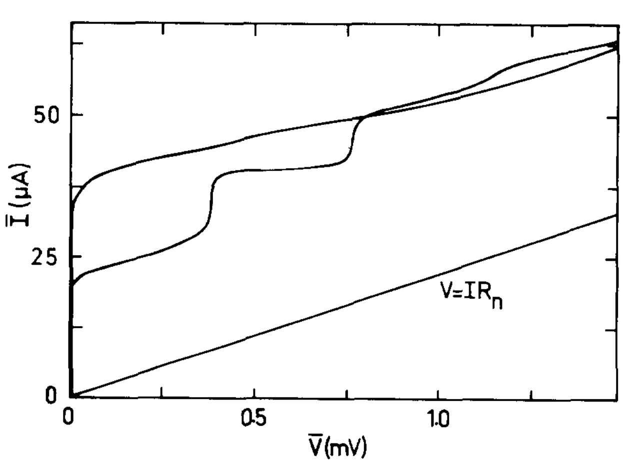

FIG. 2. Typical *I-V* curves of a low surface-pressure-type Josephson junction without radiation and exposed to 185-GHz LO power such that I_c is about 50% reduced, compared with the normal state resistance.

increase after breaking and remaking the contact. When such a contact is burned in (e.g., from 100–30 Ω) there is quite often no significant change in the hysteresis. Since burning in of the contact probably does not change the capacitance in the junction, the normalized hysteresis parameter[25] $\beta_c = 2eI_cR^2C/\hbar$ will decrease linearly with R, suggesting a decrease in the hysteresis. However, at the same time the normalized noise parameter $\Gamma = 2ek_BT/\hbar I_c$ also decreases linearly with R. This means that the noise rounding[12,26] of the I-V curve decreases, so that the actual hysteresis in the I-V curve caused by the capacitive shunt could be approximately constant for decreasing R, which is in agreement with the observations.

This reasoning can also be applied to the hysteretic contacts that Claassen *et al.*[2] obtained for other than Nb-Nb point contacts. Since they decrease their junction resistance by increasing the pressure on the contact it is possible that the decrease in R is compensated by an increase in C, thereby keeping β_c approximately constant. Because Γ again decreases for decreasing R, the hysteresis in the I-V curve will then increase for decreasing R as they observed. The presence of a fairly large capacitance in their junctions seems not impossible, considering the crude manner of fabrication. Therefore it is quite likely that the hysteresis found in their junctions is not only caused by self-heating but also by the contact capacitance.

At first sight, slightly hysteretic junctions with the high-pressure type of contacts appear to be quite useful because the development of rf-induced steps on the I-V curve can be very pronounced. An example is given in Fig. 3. However, when it is used with a voltage bias so that it can be operated as a mixer, this type of junction does not show very good mixing but shows a very large nonheterodyne response to a thermal source, in spite of the voltage bias (see Sec. VI). When this type of junction is not hysteretic but does have large values of R_d/R, it can be used as a wide-band detector with a very large responsivity. The largest responsivity that we measured is about $5*10^6$ V/W_{ext}, which is a factor of 10

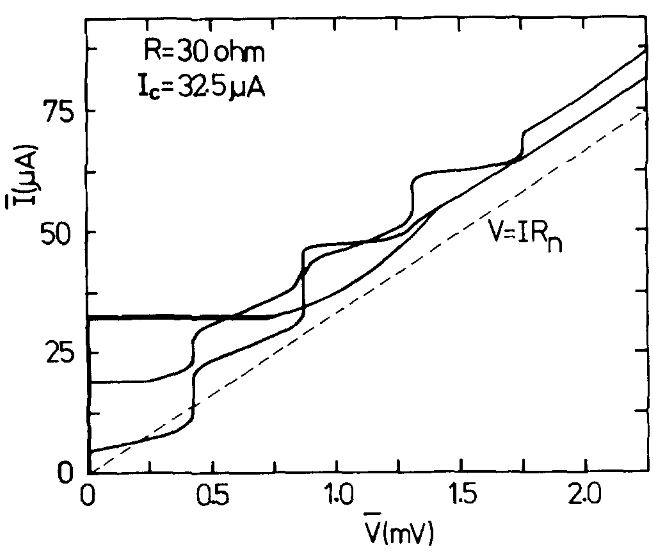

FIG. 3. Typical set of I-V curves of a relatively high surface pressure, slightly hysteretic junction exposed to increasing levels of 212-GHz radiation.

larger than reported by us earlier.[27] However, the noise characteristics were not measured in this case so that the noise equivalent power was not necessarily much better. In this case, the response was larger than the theoretical value.[28] This large wide-band responsivity is in fact responsible for the large nonheterodyne response, present even in the voltage-biased mode, as we shall see later (Sec. VI).

From a comparison of both high- and low-pressure types of contacts it is clear that only the latter are suited for heterodyne detection. This will be shown in Secs. VI and VII.

The unperturbed I-V curves show a nonlinearity at about 2.8 mV which corresponds to the gap voltage at $T = 5$ K, and a pronounced excess current with respect to $\bar{V} = \bar{I}R$. The stability of our junctions is good. They can be kept unchanged for many days when the cryostat is refilled on time. Heating of the cryostat to room temperature sometimes destroys the contact, possibly due to outgassing in the cryostat which can contaminate the junction.

V. DETERMINATION OF THE MIXER AND RECEIVER PERFORMANCE

The performance of the mixer and the receiver is determined by measuring $P_{\text{i.f.}}$ for a hot and a cold thermal source (see Sec. III). For both source temperatures, $P_{\text{i.f.}}$ can then be converted to an effective output temperature T_{out} of the mixer, with Eq. (1). T_{out} consists of two different components, the mixer noise temperature T_m referred to the input of the mixer, and the blackbody radiation temperature T_s to which the junction is exposed. Both are multiplied by the conversion efficiency η of the mixer.

$$T_{out} = \eta T_m + 2\eta T_s. \tag{2}$$

T_s is multiplied by 2 because there are two frequency bands at $\omega_{LO} \pm \omega_{\text{i.f.}}$ which are down-converted by the mixer; the mixer acts as a double-side band (DSB) mixer. When T_{out} is measured for two different values of T_s the single-side band (SSB) conversion efficiency η of the mixer is directly obtained from

$$\eta = \Delta T_{out}/2\Delta T_s. \tag{3}$$

This is done for the mixer-horn-waveguide combination with $\Delta T_s = 100 \pm 7$ K in front of the horn. Combining Eqs. (2) and (3) then results in a SSB mixer-noise temperature T_m:

$$T_m = (T_{out}/\eta) - 2T_s. \tag{4}$$

The mixer noise level at the input of the mixer can be characterized[5] by a parameter β^2 which is defined as the square of the ratio of the effective output noise current at the i.f. to the Johnson noise current associated with the shunt resistor in the Josephson junction (RSJ model); β^2 can be written as[2,4]

$$\beta^2 = (\eta T_m/T)(R/R_d). \tag{5}$$

The figure of merit for the entire receiver is the receiver noise temperature T_r. It is experimentally determined by measuring the ratio y of $P_{\text{i.f.}}$ for two different values of T_s. T_r is then obtained[29] from

$$T_r = 2(T_h - yT_c)/(y-1), \tag{6}$$

where T_h and T_c are the temperatures of the hot and cold sources, respectively. Because of the factor 2 in Eq. (6), T_r is also a SSB temperature. For this measurement it is not necessary to measure the absolute level of $P_{i.f.}$. The connection between T_r and the mixer performance itself is found when T_r is calculated with the values of T_h and T_c in front of the horn instead of in front of the Teflon lens. Then a net SSB receiver temperature T_r^* is obtained. This T_r^* is by definition equal to

$$T_r^* = (T_m + T_{i.f.}/\eta), \tag{7}$$

where $T_{i.f.}/\eta$ is the effective noise temperature of the i.f. system at the input of the mixer; $T_{i.f.}$ is obtained from the calibration of the i.f. system. T_r and T_r^* are connected by

$$T_r = (L-1)T_{phys} + LT_r^*, \tag{8}$$

where L is the loss between the outside of the dewar and the front of the horn and T_{phys} is the effective physical temperature of this loss. Both can be calculated from Table I: $L \simeq 1.52$ (1.8 dB) and $T_{phys} \simeq 80$ K.

The actual hot-cold measurement has been done in both a dc and an ac manner. In the ac mode a chopper is used with blades covered with a sheet of Eccosorb AN-72 at room temperature and with Eccosorb immersed in LN_2 behind it. This ac method is very useful in quickly finding the optimum LO-power level, bias voltage, and back-short position. Once this optimum is found the absolute value of $P_{i.f.}$ is measured for both the hot and the cold source (dc method). These values correspond to two values of T_{out} from which η, T_m, T_r, and T_r^* are calculated.

VI. NONHETERODYNE RESPONSE OF THE MIXER

The determination of the performance of the mixer and receiver as described in Sec. V will only give a reliable result when $P_{i.f.}$ is not influenced at the same time by wide-band response effects. However, not only the thermal radiation in the frequency intervals $B_{i.f.}$ at $\omega_{LO} \pm \omega_{i.f.}$ are coupled to the junction. Radiation with a bandwidth far greater than this will couple to the junction with similar efficiency. This radiation will also reduce I_c when it is already partially reduced by the LO power. When the junction is biased from a high-impedance source, V will then change, resulting in a change in $P_{i.f.}$. This response can have a positive or a negative sign and is present in addition to the heterodyne response. However, this effect can be easily suppressed by biasing the junction from a very low-impedance source,[10] thereby effectively applying a constant voltage bias. This has the additional advantage of the mixer being virtually insensitive to small variations in the LO power and a possible temperature change of the detector. In our receiver we can switch between a quasi-current bias (source impedance $R_s \simeq 10\ k\Omega$) and a quasivoltage bias ($R_s \simeq 1\ \Omega$) while at 4.2 K; the 1-Ω source impedance exists only for frequencies $\ll \omega_{i.f.}$ so that the i.f. output impedance of the mixer is not affected.

A disadvantage of the voltage bias is that it is also possible to operate slightly hysteretic junctions as mixers. This can have a very disturbing effect. We have found that for this type of junction and for junctions with a continuous I-V curve with $R_{d_{max}}/R \gg 1$, a very large nonheterodyne response to a hot-cold signal can occur, even when $\bar{V}$ is held constant. This response can have the same sign as the heterodyne hot-cold response, as opposed to the experience of others.[10] This will occur for junctions that show an anomalous behavior of $P_{i.f.}$ as a function of the LO power. This anomaly consists of a strong increase of $P_{i.f.}$ for increasing LO power or an increasing level of wide-band radiation. It can occur very locally in the I-V domain limited by $0 < \bar{V} < \hbar\omega_{LO}/2e$ and $0 < \bar{I} < I_c$. The heterodyne and wide-band response components can be discriminated by using a Michelson interferometer with a Mercury arc as a thermal source.[10] An example of this method is given in Fig. 4 for the junction of Fig. 3. The actual spectral response of $P_{i.f.}$ to a thermal source is given in Fig. 4(b) where the two spectra of Fig. 4(a) are subtracted to remove the response due to a modulation of the LO coupling by the interferometer. There is hardly any residual response at $\omega_{LO} \pm \omega_{i.f.}$. The very large hot-cold response, which was of the correct sign, is therefore not a heterodyne response but almost entirely a wide-band response. If it would have been interpreted as a heterodyne response, a noise temperature $T_r^* \simeq 100$ K would result suggesting conversion gain in the mixer (since $T_{i.f.} \simeq 180$ K) a virtual impossibility at this signal frequency. Although the junction was slightly hysteretic without LO power, the hysteresis had disappeared at the LO power level necessary to reduce I_c to about 50%; at this level the maximum response was found.

The spectrum in Fig. 4(b) is equal to the wide-band response spectrum that is obtained in the ordinary manner[27,28]

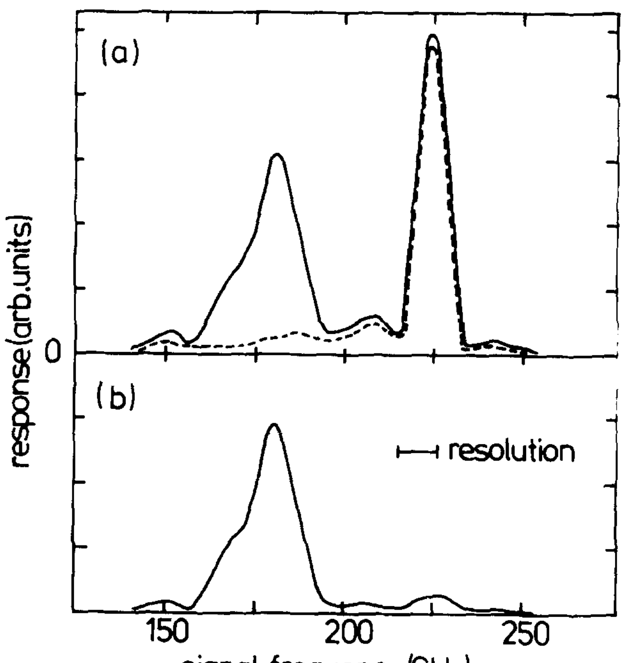

FIG. 4. Michelson spectra of the response of $P_{i.f.}$ to a thermal source for a 30-Ω junction of Fig. 3 with I_c reduced to about 50% by 225-GHz LO power and at a bias voltage of about $\hbar\omega_{LO}/4e$. (a) shows the spectrum with the Hg-arc source on (heavy line) and off (dashed line). The large peak at ω_{LO} occurs because of the modulation of the coupled LO power by the interferometer. (b) is the difference between the two spectra and gives the actual spectrum of the hot-cold response. It is clear that most of this response has no relation to ω_{LO} and is therefore a wide-band response.

same back-short position. It is almost completely determined by the spectrum of the coupling of radiation to the junction. Since the back-short was adjusted to maximize the total hot-cold response, it is to be expected that the heterodyne response in this case can be improved by optimizing the back-short for the signal frequency. However, that is not a simple procedure without a suitable monochromatic signal source. It is clear that the wide-band response spectrum can be used to find a geometry that gives optimum coupling of radiation at the intended signal frequency.

The nonheterodyne hot-cold response occurs most often for junctions that tend to have a hysteretic I-V curve and that are of the high surface-pressure type (see Secs. II and III). That means that they have larger values of $r_d = R_d/R$ than predicted by the RSJ model; this is often the only clue to a small hysteresis hidden in thermal noise.[11,12] Since the determination of the spectrum of the hot-cold response with an interferometer is the only way to make sure that the response is caused by mixing, heterodyne measurements that show conversion in an anomalous way and that have not been checked with an interferometer[13,14] are suspicious.

VII. HETERODYNE RESPONSE

With our low surface-pressure contacts it is possible to make Josephson junctions that exhibit very good mixing results at a frequency of about 200 GHz. The parameters of a representative set of junctions are given in Table II for an LO frequency of 185 GHz; for LO frequencies of 207 and 220 GHz only the performance of the best junction at each frequency is given. The performance was measured each time with the hot-cold response, the spectrum of which was verified with a Michelson interferometer. It always consisted for more than 95% out of a heterodyne response. The effect of a changing r_d in the bias-point, caused by wide-band response to the thermal source (as found by Claassen *et al.*[2,5]) hardly occurred in our measurements. Its influence on the change

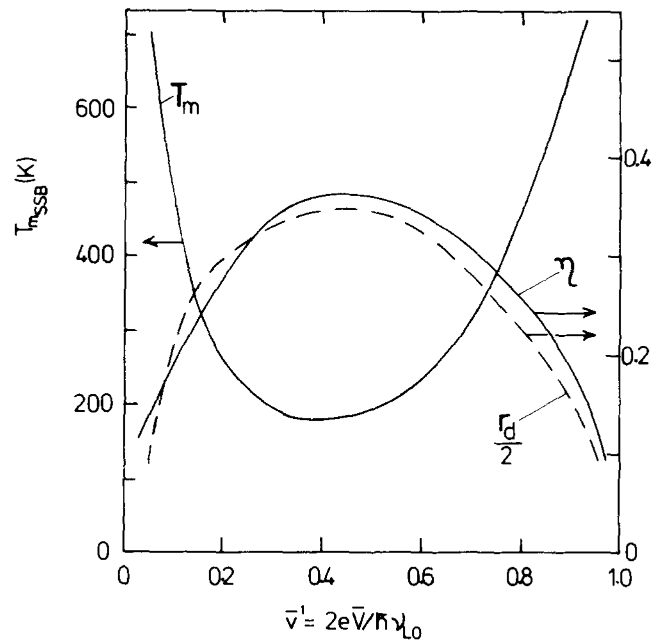

FIG. 5. Dependence of η, T_m, and r_d on the bias voltage for a junction with $R = 80\,\Omega$ and $I_c = 16\,\mu$A at a temperature of 5 K. $\nu_{LO} = 185$ GHz so that the normalized signal frequency is $\Omega_s = 0.3$.

of $P_{i.f.}$ was always smaller than 5% of the change of $P_{i.f.}$ by the heterodyne response. This may be partially due to the low values of r_d for which the change in r_d by noise rounding is always small, and also due to the small dependence of $T_{i.f.}$ on R_d near the optimum resistance value.

An example of the behavior of T_m, η, and r_d on the bias voltage is shown in Fig. 5 for a typical junction at a temperature of 5 K. An accurate comparison of our results with calculations based on the RSJ model[5,22,30] is not possible for several reasons. First of all, our values of T_m, η, and β^2 are measured for the mixer including the waveguide structure

TABLE II. The important parameters of a number of low-pressure-type junctions used as mixers. For 185 GHz a representative set is given, while for both 207 and 220 GHz the performance of our best junction at each frequency is given. All 14 are different junctions, notwithstanding the fact that the resistance values are sometimes identical. The normalized signal frequency Ω_s is in each case 0.25–0.30 and the junction temperature is 5 K. The performance is always measured with the hot-cold response only. For all parameters the SSB values are given. In the values for η, T_m, β^2 and T^*_{rSSB} the losses in the mixerblock-horn combination are included. The values for T_{rSSB} include all losses between the mixer and the outside of the receiver. They are given for both the current i.f. system and the planned low-noise FET amplifier.

nr.	$R\,(\Omega)$	$R_d\,(\Omega)$	η_{SSB}	T_{mSSB}(K)	β^2	T^*_{rSSB}	T_{rSSB}(K) ($T_{i.f.} \cong 180$ K)	T_{rSSB}(K) ($T_{i.f.} = 20$ K)	ν(GHz)
1.	55	60	0.24	290	13	1040	1660	650	185
			0.15	640	18	1840	2880	1250	220
2.	56	40	0.36	165	17	665	1090	415	185
3.	125	150	0.14	680	16	2500	3800	1330	185
4.	56	75	0.28	450	19	1160	1850	870	185
5.	44	60	0.37	265	14	750	1220	565	185
6.	56	60	0.23	215	9	1000	1600	540	185
7.	45	40	0.24	200	11	950	1520	510	185
8.	60	40	0.17	380	19	1440	2260	840	185
9.	65	45	0.15	310	13	1600	2500	750	185
10.	55	36	0.14	180	8	1700	2660	570	185
11.	80	56	0.36	180	18	680	1110	440	185
12.	80	40	0.36	250	14	820	1320	540	185
13.	50	45	0.38	210	18	690	1130	480	207
14.	50	70	0.40	240	14	730	1190	520	220

and the microwave horn of which we cannot measure the losses; a loss of 2 dB, however, seems not unrealistic. Furthermore our mixer is not protected by cooled narrow-band signal filtering, so that it is exposed to a high background level of thermal radiation in contrast with the situation in the calculations. Finally, there is some discrepancy between the results of different authors and also some unclarity about a possible divergence in η which can occur[22] in connection with a significantly larger T_m for a very specific value of Ω_s and Γ. The high conversion efficiency shown in Fig. 7 of Ref. 22, for instance, is apparently chosen so that it occurs directly next to the divergence at $\Gamma = 0.006$ (Fig. 8 of Ref. 22). It is not clear whether such a divergence will occur in an actual Josephson mixer.

A qualitative comparison between the calculations[5,22,30] and our results is possible, however. In our junctions there is always a rather smooth maximum in η and a smooth minimum in T_m for an LO power such that the supercurrent is reduced to about (0.4–0.8) I_c as expected from the RSJ model.[5] This in contrast with the nonheterodyne response described in Sec. VI.

In comparing the experimental mixer-noise temperature with the RSJ model we see that the lowest value $T_m = 165$ K in Table II results in $T_m/T \simeq 35$, which is similar to that calculated by Claassen *et al.*[5], but a factor of three larger than calculated by Taur.[22] The dependence of T_m on the average-bias voltage normalized with respect to the voltage of the first rf-induced step, $\bar{v} = \bar{V}(\hbar\omega_{LO}/2e)^{-1}$, shows a minimum somewhat below $\bar{v} = 0.5$, which is in good agreement with the RSJ model.[5,22] The typical accuracy of T_m is 20–25%.

The conversion efficiency η always shows a maximum for $\bar{v} \simeq 0.5$, in agreement with the RSJ model. The absolute values of η are in rather good agreement with the calculations[5,22,30] when the effects of a divergence are omitted. For each junction η is approximately proportional to r_d, which is in agreement with the analog computer calculations of Claassen *et al.*[5]; see Fig. 5 where r_d is shown for comparison with η. The typical accuracy of η is about 10%.

The values for the noise parameter β^2 in Table II are about 2–3 times the values obtained by Claassen *et al.*[4,5] from their electronic simulator of the RSJ model. This cannot be explained by the effect of external thermal radiation because in Eq. (4) this influence is taken into account by subtracting $2T_s$ from T_{out}/η, so that in Eq. (5) only the internal noise is represented by T_m. Our values of β^2, however, are only a little larger than that found by others[4,5] for the same value of Ω_s. Since η is proportional to r_d, it follows from Eq. (5) that β^2 is proportional to T_m. The dependence of β^2 on $\bar{v}$ therefore shows a minimum for $\bar{v} \simeq 0.5$, in agreement with the dependence expected from the RSJ model.[4,5]

From this comparison it can be concluded that there is a good qualitative agreement between our results and the RSJ model. In addition the quantitative results show no large discrepancy, certainly when the losses in the mixerblock-horn system would be taken into account.

From the measurements it appears that there is an optimum value of R and R_d around 50–60 Ω in our mixer design. This optimum is not influenced by the fact that $T_{i.f.}$ is minimum at an input impedance of about 50 Ω because in the calibration described in Sec. III B the IF coupling of the mixer with the i.f. system is already taken into account. The optimum could be caused by an optimum in the coupling of radiation to the junction when its resistance is above 50 Ω, while the conversion increases[22] for a lower value of Γ occurring at lower values of R ($\Gamma \sim R^{-1}$). This might explain the higher value of optimum R in our case compared with an optimum value of about 30 Ω found by Taur *et al.*[3] in a reduced height waveguide with a lower characteristic impedance than the full height waveguide in our system.

Table II also gives the SSB values of T_r and T_r^* for our system with the parametric amplifier as a first stage i.f. amplifier ($T_{i.f.} \simeq 200$ K at the mixer). If a state of the art cooled FET amplifier ($T_{i.f.} = 20$ K) was incorporated in our system the resulting values of T_r ($T_{i.f.} = 20$ K) for the total system can be calculated from Eqs. (7) and (8). They are also given in Table II. In that case the best value of the SSB receiver-noise temperature T_r ($T_{i.f.} = 20$ K) would be as low as 400–500 K for a signal frequency of 170–220 GHz. The instantaneous bandwidth is about 20 GHz so that to span the entire frequency range it is necessary to slightly adapt the configuration of anvil and whisker-post to optimize the coupling at the desired frequency.

VIII. CONCLUSION

We have found that point-contact Josephson junctions can be excellent high-frequency mixers under high background levels when the junctions are made with a sufficiently low surface pressure. In the geometry that we used, the best junction that was produced showed a SSB mixer-noise temperature of 165 K ($\pm 25\%$) with a SSB conversion efficiency of 0.36 ± 0.03 (a loss of 4.5 ± 0.4 dB) at a signal frequency of 185 GHz. In this figure the losses caused by the microwave horn, the waveguide, and the back-short are included so that the actual mixer performance is even better. This performance is comparable to what may be expected from the RSJ model. When this best junction is used in our receiver with a state of the art low-noise i.f. amplifier ($T_{i.f.} = 20$ K) a SSB receiver-noise temperature of 415 K is reached. With a small geometrical adaptation of the junction electrodes the receiver can be used in different intervals of the full frequency range of 170–220 GHz; the instantaneous bandwidth is then about 20 GHz. The stability of our junctions is good enough that they can be used on a telescope.

Also an important result is that when high-pressure-contact Josephson junctions are used, a very strong non-heterodyne response to a hot-cold signal can occur, even in the voltage-biased mode. This response can be of the same sign as the heterodyne response and can easily be mistaken for it. It can suggest a much better heterodyne performance than is actually the case.

Our Josephson heterodyne receiver is the first to show a good behavior as a high-frequency mixer at a high thermal-background level. This is in contrast to other receivers[2,3] at lower signal frequencies that incorporated cooled lossy elements to reduce the influence of room-temperature wide-band radiation.

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[1]Y. Taur, J. H. Claassen, and P. L. Richards, Appl. Phys. Lett. **24**, 101 (1974).
[2]J. H. Claassen and P. L. Richards, J. Appl. Phys. **49**, 4130 (1978).
[3]Y. Taur and A. R. Kerr, Appl. Phys. Lett. **32**, 775 (1978).
[4]J. H. Claassen, Y. Taur, and P. L. Richards, Appl. Phys. Lett. **25**, 759 (1974).
[5]J. H. Claassen and P. L. Richards, J. Appl. Phys. **49**, 4117 (1978).
[6]D. N. Held and A. R. Kerr, IEEE Trans. Microwave Theory Tech. **26**, 49 (1978), and **26**, 55 (1978).
[7]P. L. Richards, T. M. Shen, R. E. Harris, and F. L. Lloyd, Appl. Phys. Lett. **34**, 345 (1979).
[8]P. L. Richards and T. M. Shen, IEEE Trans. Electron Devices **ED-27**, 1909 (1980).
[9]G. J. Dolan, R. A. Linke, T. C. L. G. Sollner, D. P. Woody, and T. G. Phillips, IEEE Trans. Microwave Theory Tech. **29**, 87 (1981).
[10]T. G. Blaney, "A Theoretical and experimental study of Josephson frequency mixers for heterodyne reception in the sub-mm wavelength range," Internal report of The National Physics Laboratory (NPL), United Kingdom, 1978, S. I. No. 89/0382.
[11]J. Kürkijärvi and V. Ambegaokar, Phys. Lett. A **31**, 314 (1970).
[12]T. Poorter and H. Tolner, J. Appl. Phys. **51**, 6305 (1980).
[13]J. Edrich, D. B. Sullivan, and D. G. McDonald, IEEE Trans. Microwave Theory Tech. **25**, 476 (1977).
[14]G. M. Daalmans, Th.de Graauw, S. Lidholm, and Fr. van Vliet, in *SQUID 80*, edited by H. D. Hahlbohm and H. Lübbig (Walter de Gruyter, Berlin, 1980), p. 863.
[15]H. Diepers, O. Schmidt, H. Martens, and F. S. Sun, Phys. Lett. A **37**, 139 (1971).
[16]R. W. Haas and B. Vowinkel, Technischer Bericht nn 46, Max Planck Institut Für Radio Astronomie, Bonn, West Germany.
[17]Deltabond 152a, Manufactured by Wakefield Engineering, Inc. Massachusetts.
[18]Cyanobond RP; Manufactured by Sumito Chemical Co. Ltd., Osaka, Japan; soluble in acetone.
[19]Infrared Laboratories, model HD-3.
[20]R. Adde and G. Vernet, in *Future Trends in Superconductive Electronics* edited by B. S. Deaver, Jr. *et al.* (AIP Conf. Proc. New York, 1978), Vol. 44, p. 239.
[21]V. Ambegaokar and A. Baratoff, Phys. Rev. Lett. **10**, 486 (1963) and **11**, 104 (1963).
[22]Y. Taur, IEEE Trans. Electron Devices **ED-27**, 1921 (1980).
[23]H. Tolner, J. Appl. Phys. **48**, 691 (1977).
[24]M. Tinkham, M. Octavio, and W. J. Skocpol, J. Appl. Phys. **48**, 1311 (1977).
[25]D. E. McCumber, J. Appl. Phys. **39**, 3113 (1968); W. C. Stewart, Appl. Phys. Lett. **12**, 277 (1968).
[26]V. Ambegaokar and B. I. Halperin, Phys. Rev. Lett. **22**, 1364 (1969).
[27]T. Poorter and H. Tolner, Infrared Phys. **19**, 317 (1979).
[28]H. Kanter and F. L. Vernon, J. Appl. Phys. **43**, 3174 (1972).
[29]*Handbook of Microwave Measurements*, 3rd ed., edited by M. Sucher and J. Fox (Polytechnic, Brooklyn, 1963), Vol. III, p. 881.
[30]V. P. Zavaleyev and K. K. Likharev, Radio Eng. Electron. Phys. **24**, 103 (1979).